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ABSTRACT

Twenty-five years of tropical cyclone data (1945–69) for the western North Pacific were evaluated to determine the speed-of-movement characteristics of tropical storms and typhoons following recurvature. The results show that the acceleration of storms following recurvature is dependent on the meteorological characteristics of the storm, and the surrounding synoptic environment which is a function of the time of the year. Forecast equations derived by linear regression techniques are presented for the speed of movement of tropical cyclones 36 hr after recurvature.

1. Introduction

One of the major problems encountered by a tropical cyclone forecaster is the recurving tropical storm or typhoon. He has to determine whether the storm will recurve or continue heading on a generally east-west track. If the forecaster is confident it will recurve he then has to determine the point of recurvature; that is, the point at which the storm changes its path from westerly to easterly movement. Finally, he must forecast the speed and direction of the storm after recurvature.

As the storms move northeastward, they accelerate (on the average) within a period of 48 hr to speeds two to three times that at their point of recurvature. With such changes in speed of movement, forecast errors increase sharply. This can be seen in Table 1, which presents average 24-hr forecast statistics for typhoons from 1961–69. The average annual 24-hr forecast error for all 183 typhoons in this 9-year period was 128 n mi. For the 77 typhoons that recurved, however, the average error was 141 n mi. The difficulty in forecasting northeastward moving storms is further reflected in the 165 n mi average error for forecasts verifying after the point of recurvature.

TABLE 1. Average 24-hr forecast statistics for the typhoons from 1961–69.

Average annual 24-hr forecast error (all typhoons)	Average 24-hr forecast error for recurving typhoons	Average 24-hr forecast error for recurving typhoons for the forecast positions verifying after the point of recurvature
128 n mi 183 typhoons 3600 forecasts	141 n mi 77 typhoons 1819 forecasts	165 n mi 77 typhoons 707 forecasts

It is evident from the statistics presented in Table 1 that the movement prediction error for storms that recurve is greater than average. It should be noted that the average annual error includes storms that have recurved. Thus, the difference would be even more striking if the recurving and non-recurving storms were considered separately.

The purpose of this paper is to familiarize the forecaster with the speed-of-movement characteristics of recurved tropical cyclones. This information, in conjunction with conventional prediction techniques and knowledge of the intensity changes of recurved tropical cyclones (Riehl, 1972), should be a useful forecast aid to the tropical cyclone forecaster.

2. Data and method of analysis

In this study tropical storms[1] and typhoons[2] occurring in the months of May–December, 1945–69, were examined. Of the 586 tropical storms and typhoons in this period, 236 (40%) recurved. Selection of recurving storms was based on the criteria that they 1) achieved tropical storm or greater intensity at one time in the life of the storm, and 2) had a basically westerly heading which recurved to a basically easterly heading. Those storms experiencing a loop at the time of recurvature were not considered.

Table 2 presents a comparison of the recurving tropical storms and typhoons with the total number of tropical storms and typhoons as separated by monthly and half-monthly periods. It can be seen that the percentage frequency of recurving tropical storms and

[1] Tropical cyclonic circulation which attains tropical storm intensity (34–63 kt) at one time in the life of the storm.

[2] Tropical cyclonic circulation which attains typhoon intensity ($\geqslant 64$ kt) at one time in the life of the storm.

typhoons is greater than 50% in the early and late tropical cyclone season with a minimum of approximately 20% occurring in July.

The following meteorological parameters were examined for each 6-hr position of the recurving tropical storms and typhoons:

Intensity (maximum surface wind)
Speed of movement
Direction of movement
Size (circulation size as indicated by average diameter of outer closed surface isobar)
Strength and position of 700-mb ridge north of storm
Strength and position of 700-mb trough west of storm at 35N.

These parameters were related to the speed of movement at and after the point of recurvature of the selected storms.

3. Discussion of results

Recurving tropical cyclones have a marked seasonal variation as the storms respond to seasonal changes of the synoptic environment. Fig. 1 presents the seasonal variation (May–December) of a number of parameters associated with the points of recurvature for the 236 recurving tropical cyclones.[3] Fig. 1(a) shows that the average latitude of recurvature moves northerly through August and moves southerly thereafter. This is consistent with the findings of Riehl (1972) who examined the intensity of 66 recurving typhoons for the period 1957–68. The average longitude of recurvature (shown in brackets) moves toward the east through October and then sharply returns to the west in November and December.

The average speed of movement at recurvature [Fig. 1(b)] is slightly over 10 kt; below-average values occur toward the end of the tropical cyclone season and also in August.

The seasonal variation of the size of the tropical storms and typhoons at the point of recurvature [Fig. 1(c)] shows a general increase in circulation size (average diameter of outer closed surface isobar) through October with a decrease thereafter. It should be mentioned that typhoons (both recurving and nonrecurving) have been found to be largest in October (Brand, 1972).

The intensity [Fig. 1(d)] shows an average value near 80 kt, with the first half of the season being below average and the second half above average. August again stands out as an unusual month with an apparent dip in the general seasonal trend. Riehl (1972) also found August typhoons to be weaker systems at the point of recurvature.

In order to examine the speed of movement of the recurved tropical cyclones in question, a ratio (R_s) was developed to normalize the actual speed of movement (S) after recurvature relative to the speed of movement at the point of recurvature (S_r). That is,

$$R_s = \frac{S}{S_r}. \tag{1}$$

[3] It should be noted that one November tropical cyclone experienced recurvature twice.

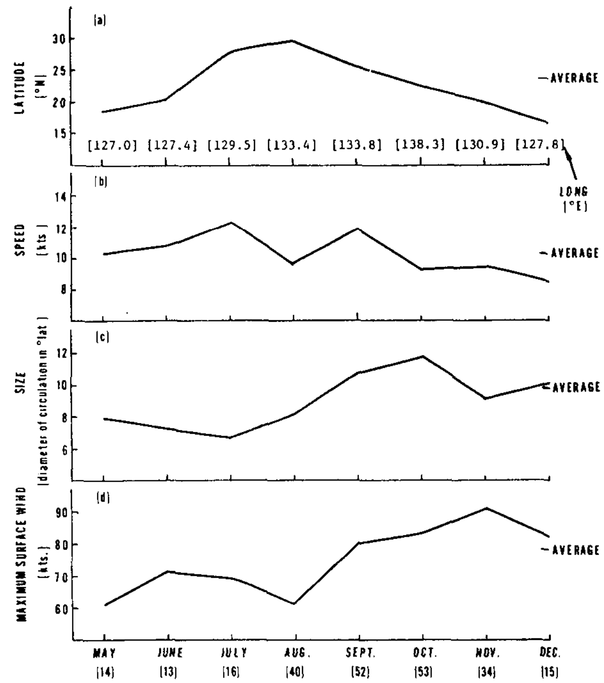

Fig. 1. Seasonal variation at point of recurvature of (a) latitude and longitude [in brackets], (b) speed of movement, (c) size, and (d) maximum surface wind for the recurving tropical storms and typhoons from May–December (1945–69). The number in brackets below each month is the number of recurving tropical storms and typhoons observed for each month. The size parameter is the diameter of circulation as deduced from the average diameter of the outer closed surface isobar.

Table 2. Recurving tropical storms and typhoons and total number of tropical storms and typhoons by monthly or half-monthly periods for the years 1945–69. Storms are categorized according to midpoint in time of total storm track.

Period	Recurvers per period	Total tropical storms and typhoons per period	Percent that recurve
May	14	24	58
Jun	14	40	35
Jul 1–15	7	34	21
Jul 16–31	10	54	19
Aug 1–15	15	51	29
Aug 16–31	24	62	39
Sep 1–15	32	70	46
Sep 16–30	21	53	40
Oct 1–15	24	46	52
Oct 16–31	28	48	58
Nov 1–15	20	36	56
Nov 16–30	14	34	41
Dec	13	34	38
May–Dec	236	586	40

TABLE 3. Average monthly values of R_s (standard deviation in brackets) as a function of time after recurvature for tropical storms and typhoons from 1945–69. The number of observations is given in parentheses.

	Time after recurvature											
		12 hr			24 hr			36 hr			48 hr	
Period	R_s	[σ]	(obs)	R_s	[σ]	(obs)	R_s	[σ]	(obs)	R_s	[σ]	(obs)
May	1.11	[0.36]	(14)	1.46	[0.76]	(13)	1.88	[1.46]	(11)	2.23	[1.76]	(10)
Jun	1.37	[0.36]	(13)	1.52	[0.59]	(12)	1.77	[0.72]	(10)	1.69	[0.54]	(7)
Jul	1.17	[0.38]	(15)	1.27	[0.55]	(13)	1.74	[1.24]	(7)	2.30	[1.77]	(5)
Aug	1.30	[0.40]	(38)	1.58	[0.58]	(31)	1.81	[0.75]	(25)	2.09	[1.08]	(16)
Sep	1.34	[0.42]	(49)	1.78	[0.77]	(40)	2.29	[1.20]	(29)	2.32	[1.59]	(21)
Oct	1.35	[0.41]	(53)	1.87	[0.86]	(45)	2.32	[1.25]	(38)	2.64	[1.46]	(29)
Nov	1.51	[0.59]	(34)	2.00	[0.93]	(29)	2.60	[1.28]	(24)	2.95	[1.58]	(15)
Dec	1.32	[0.37]	(14)	2.04	[0.96]	(13)	2.86	[1.26]	(10)	2.98	[2.12]	(5)

Average values and standard deviations of R_s were computed at specified times (12, 24, 36, 48 hr) after recurvature for each month (May–December); the results are given in Table 3. In general, it can be seen, even with these relatively small samples, that the averages increase from one specified time to the next and from one month to the next, with quite a large seasonal variation. For example, a July storm with a speed of 10 kt at the point of recurvature would be traveling at a speed of 12.7 kt in 24 hr (using the average R_s value of 1.27); in November, the average R_s value of 2.00 indicates that the 10-kt storm would accelerate dramatically to 20 kt in 24 hr.

It is obvious that the increase in average speed of the storms after recurvature is different for each month. The question then arises as to whether the speeds are related to the upper level flow which also shows seasonal variation. Table 4 presents the average monthly values (May–December) of the zonal (west-to-east) component of the speed of movement (S_z) given as a function of 5° latitude bands for recurved tropical storms and typhoons from 1945–69. In general, it can be seen that the zonal component of the speed of movement increases to the north. The last column of Table 4 (all latitude bands) shows a low rate of west-to-east movement of August storms with a dramatic increase occurring in September. This increase can be partially explained by the increase in the zonal component of the upper level flow as shown by Fig. 2, which shows S_z values (only plotted if 10 or more observations were available) and the monthly averaged 300-mb zonal flow plotted as a function of latitude for the months August–November (the months with the greatest number of recurving storms). The 300-mb zonal flow is derived from 5° grid point values for 120–170E and 10–40N [reduced from the mean-monthly climatologies of Sadler and Harris (1970) and Sadler (1972)].

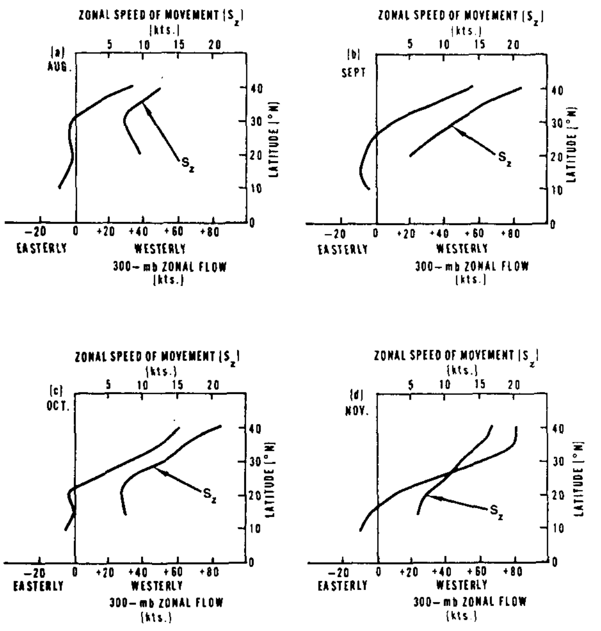

FIG. 2. Zonal (west-to-east) component of the speed of movement (S_z) of recurved tropical storms and typhoons (1945–69) and the 300-mb zonal flow plotted as a function of latitude for the months of (a) August, (b) September, (c) October, and (d) November (see Table 4). The 300-mb zonal flow is derived from 5° grid point values from 120–170E and 10–40N.

Notice that the north-south variations of S_z are in good agreement with the variations of the 300-mb zonal flow.

An important consideration in examining recurving storms is the direction of movement of the storms after recurvature. This is important because the forecast position is not only related to the speed of movement but also to the direction of movement. Additionally, the forecaster many times accurately determines the future direction of movement of a recurved storm only to find the storm accelerating out of the range of an otherwise acceptable forecast. In order to examine this speed-vs-direction relationship, the speed of movement of recurved storms was plotted as a function of direction of movement; the results are shown in Fig. 3. The speed-of-movement values (solid line), averaged for each 10° movement category (centered on the values given), show that the greatest speeds occur for storms with a direction heading of 50°–60°.

If acceleration[4] is plotted in a similar manner (dashed line of Fig. 3), it can be seen that the greatest accelera-

[4] Acceleration is defined here as the increase in speed of movement occurring from one observation to the following 6-hr observation.

Table 4. Average monthly observed values of the zonal (west-to-east) component of the speed of movement (S_z) as a function of 5° latitude bands for recurved tropical storms and typhoons from 1945–69. Averages are also presented for all months (May–December) and for all latitude bands combined. Speeds are given in knots, number of observations are shown in parentheses.

	Latitude bands (°N)						
Period	12.5–17.4	17.5–22.4	22.5–27.4	27.5–32.4	32.5–37.4	37.5–42.4	12.5–42.4
May	6.5 (10)	6.4 (65)	10.3 (49)	11.9 (31)	24.1 (7)	0 (0)	9.4 (162)
Jun	0 (0)	10.1 (29)	11.6 (45)	13.7 (36)	12.3 (22)	20.7 (4)	12.2 (136)
Jul	0 (0)	10.0 (2)	9.7 (19)	10.0 (36)	13.5 (39)	13.7 (15)	11.7 (111)
Aug	4.9 (2)	9.2 (11)	8.2 (26)	6.9 (103)	8.9 (129)	12.6 (50)	8.9 (330)
Sep	0 (0)	5.2 (20)	7.9 (94)	12.1 (119)	15.4 (116)	21.1 (44)	12.7 (393)
Oct	7.2 (14)	6.8 (97)	7.9 (178)	13.2 (156)	16.1 (88)	21.2 (22)	11.0 (555)
Nov	6.0 (16)	6.9 (91)	10.5 (89)	12.4 (67)	15.6 (21)	16.9 (3)	10.0 (287)
Dec	6.3 (21)	7.6 (61)	9.8 (32)	21.0 (4)	35.1 (2)	19.9 (3)	9.1 (123)
May–Dec	6.4 (63)	7.1 (376)	9.1 (532)	11.5 (552)	13.5 (424)	16.9 (150)	10.7 (2097)

tion takes place with a storm heading of 40°–50°. This would be just prior to the time the storms achieved their greatest speeds, as they veered from northeast to east-northeast.

This veering can be seen in Fig. 4 which presents the percentage frequency distribution of direction of movement at specified times relative to the point of recurvature. Distributions are given for 24 hr prior to and 24 and 36 hr after the point of recurvature for the periods: (a) May–July, (b) August–September, (c) October–December, and (d) May–December (all months). The mean headings (heavy arrows) show the storms veering, on the average [Fig. 4(d)], about 83° in the time period from 24 hr prior to recurvature to 24 hr after recurvature. Less veering occurs in the early season (70°) than in the late season (95°) [cf. Figs. 4(a) and 4(c)].

To predict the speed of movement of the recurved storms for a specified time after the point or recurvature, the forecaster could use the values presented in Table 3 as an initial estimate. For example, by re-arranging Eq. (1), a forecast equation for the speed of movement 36 hr after the point of recurvature can be given in the form

$$S_{36}=R_s\times S_r, \qquad (2)$$

where R_s is the appropriate monthly value (from 36 hr column of Table 3) and S_r the speed of movement at the point of recurvature. To further improve the prediction of the speed after recurvature, a number of parameters were examined to see if a better R_s value, other than the average, could be derived using regression techniques.

Equations were developed using a stepwise regression program with R_s as the dependent variable. The following 12 parameters were evaluated as possible independent variables:

S_r storm speed of movement at recurvature

I_r storm intensity (maximum surface wind) at recurvature

D_r storm size at recurvature (average diameter of outer closed surface isobar)

ϕ_r storm latitude at recurvature

λ_r storm longitude at recurvature

ΔI difference in storm intensity from value at recurvature to value 24 hr prior to recurvature ($\Delta I=I_r-I_{-24}$)

ΔS difference in storm speed of movement from value at recurvature to value 24 hr prior to recurvature ($\Delta S=S_r-S_{-24}$)

ΔD difference in storm size from value at recurvature to value 24 hr prior to recurvature ($\Delta D=D_r-D_{-24}$)

$\Delta\phi$ difference in storm latitude from value at recurvature to value 24 hr prior to recurvature ($\Delta\phi=\phi_r-\phi_{-24}$)

$\Delta\lambda$ difference in storm longitude from value at recurvature to value 24 hr prior to recurvature ($\Delta\lambda=\lambda_r-\lambda_{-24}$)

$\Delta\phi_{\text{ridge}}$ difference in latitude of the 700-mb ridge position due north of storm to latitude of storm position at the time of recurvature ($\Delta\phi_{\text{ridge}}=\phi_{\text{ridge}}-\phi_r$)

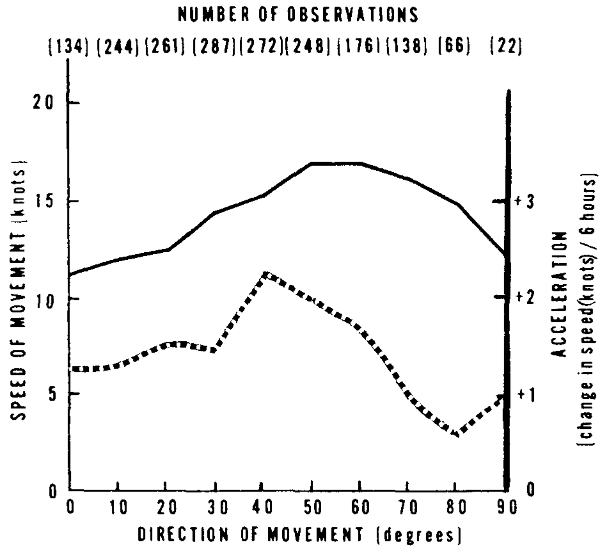

Fig. 3. Speed of movement (solid line) and acceleration (dashed line) of recurved tropical storms and typhoons (May–December, 1945–69) plotted as a function of direction of movement. The speed of movement and acceleration values have been averaged for each 10° movement category, centered on the values presented; the number of observations available is given in brackets.

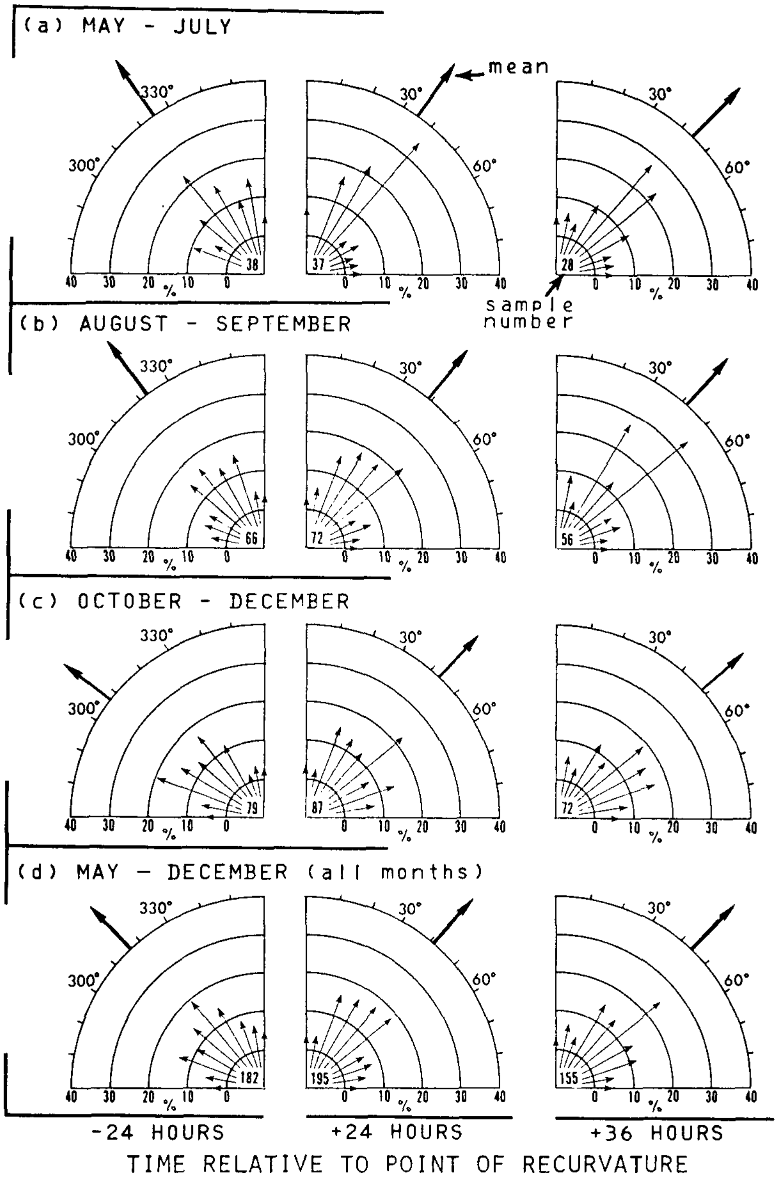

FIG. 4. Percentage frequency distributions of direction of movement at specified times relative to point of recurvature for tropical storms and typhoons from 1945–69 for the periods (a) May–July, (b) August–September, (c) October–December, and (d) May–December (all months). The sample number of "recurvers" is given at the center of the quadrants. The cumulative percentage may not necessarily add up to 100% because a small percentage may fall outside the given quadrants. Mean directions are indicated by arrows at outer boundaries of the quadrants.

$\Delta\lambda_{trough}$ difference in longitude of the storm at the point of recurvature to the longitude of the nearest 700-mb trough to the west of the storm at 35N ($\Delta\lambda_{trough} = \lambda_r - \lambda_{trough}$)

In order for a new R_s value to be accepted in place of the mean, the following criteria had to be met: 1) the regression equation for R_s had to have a correlation coefficient above 0.7; 2) the resulting values had to be significantly closer to the actual values of R_s than the mean values (5% level of F-ratio test); and 3) the new R_s value had to achieve 1) and 2) with as few variables as possible.

The results can be seen in Table 5 which presents forecast equations for predicting the speed of movement 36 hr after the point of recurvature for tropical storms and typhoons of the western North Pacific. It can be seen that no regression could be developed for September and December which gave results closer to the actual value of R_s than the mean value based on the above criteria. May, June and July have been combined and

Table 5. Forecast equations for predicting the speed of movement of tropical storms and typhoons 36 hr after the point of recurvature.

MONTH	FORECAST EQUATION
May, June, July	$S_{36} = (4.87 - 0.22S_r - 0.01I_r + 0.14\Delta S - 0.22\Delta D)S_r$
August	$S_{36} = (-3.81 + 0.16\phi_r + 0.09D_r + 0.12\Delta S - 0.19\Delta D)S_r$
September	$S_{36} = 2.29S_r$
October	$S_{36} = (1.41 + 0.57S_r + 0.01I_r - 0.19\Delta S - 1.77\Delta\phi + 0.48\Delta\lambda + 0.03\Delta\lambda_{trough})S_r$
November	$S_{36} = (3.55 - 0.14S_r + 0.16D_r + 0.02\Delta I + 0.31\Delta\lambda - 0.04\Delta\lambda_{trough})S_r$
December	$S_{36} = 2.86S_r$

DEFINITION OF PARAMETERS

S_{36} - Speed of movement of storms 36 hours after point of recurvature (knots)

S_r - Speed of movement at point of recurvature (knots)

I_r - Storm intensity (maximum surface wind) at recurvature (knots)

D_r - Storm size at recurvature (average diameter of outer closed surface isobar in degrees latitude)

ϕ_r - Storm latitude at recurvature

ΔI - Storm intensity at recurvature minus value 24 hours prior to recurvature. That is, $\Delta I = I_r - I_{-24}$ (knots).

ΔS - Storm speed of movement at recurvature minus value 24 hours prior to recurvature. That is, $\Delta S = S_r - S_{-24}$ (knots).

ΔD - Storm size at recurvature (average diameter of outer closed surface isobar) minus value 24 hours prior to recurvature. That is, $\Delta D = D_r - D_{-24}$. (degrees latitude)

$\Delta\phi$ - Storm latitude at recurvature minus value 24 hours prior to recurvature. That is, $\Delta\phi = \phi_r - \phi_{-24}$.

$\Delta\lambda$ - Storm longitude at recurvature minus value 24 hours prior to recurvature. That is, $\Delta\lambda = \lambda_r - \lambda_{-24}$.

$\Delta\lambda_{trough}$ - Storm longitude at recurvature minus the longitude of the nearest 700-mb trough to the west of the storm (at 35N). That is, $\Delta\lambda_{trough} = \lambda_r - \lambda_{trough}$.

one equation is presented which applies for recurved storms in this 3-month period.

4. Some synoptic considerations

Following completion of the statistical studies, synoptic analyses were examined to "tune" the statistical relationships discussed in Section 3. The recurving tropical storms and typhoons from May–December, 1962-69, were examined using the analyses from the U. S. Fleet Weather Central/Joint Typhoon Warning Center, Guam, and the Japanese Meterological Agency for all available significant levels from the surface to 300 mb. The conclusions derived from these analyses will be given in general terms and can be used to modify subjectively the previously discussed results. Except where otherwise indicated, comments will refer to the 700-mb level.

A prerequisite for the occurrence of recurvature was a weakness in the ridge to the north of the storm at all levels. This allowed the tropical cyclones to move northward and to interact with the westerlies.

It became obvious from the synoptic examination that there were two basic synoptic situations for the recurving storms. These two situations were particularly evident in the September–November period. One led to a slower acceleration in 36 hr than the average and the other led to a more rapid acceleration than average. The two situations can be synoptically summarized as follows:

a. Small acceleration

1. A trough, whose cyclonic circulation is further to the north than the position of the storm in question,

moves in from the west to approximately the longitude of the storm.

2. The circulation of the storm is then engulfed into the trough.

3. The storm drifts northward for approximately 24 hr and then starts to recurve to the northeast with a lower than average 36-hr R_s value.

4. Approximately 24 hr prior to becoming extratropical these systems exhibit a sharp increase in acceleration as they veer more to the northeast.

b. Large acceleration

1. A trough, whose cyclonic circulation extends south of the storm latitude, moves to within 10° longitude west of the storm position (longitude of trough measured at 35N).

2. The storm finds itself between the trough to the west and a ridge to the northeast. When the storm becomes a short wave on the trough it will recurve.

3. These storms accelerate with above-average 36-hr R_s values and continue to rapidly accelerate as they become extratropical.

In watching the life cycle of the many recurving tropical cyclones it was observed that many appeared in cycles of two storms. This was found to be particularly common in September and October. Most of the binary storms found in these months were not "Fujiwhara" systems, which have definitive interactions within 800 n mi (Brand, 1970), but seemed to be interacting with the larger scale flow pattern. Thus, for example, a storm moving to the west would soon be followed by another storm to the east of the first storm. The westerly storm would soon find itself engulfed in a trough with the easterly storm near the eastern edge of the deepening trough and with a well-developed ridge to its northeast. The result would be a northward acceleration for the second storm. Some synoptic considerations for these binary recurving systems are as follows:

1) A trough moves in from the west and engulfs the westernmost storm in a manner similar to a slowly accelerating storm described previously.

2) The westernmost storm begins moving northward and then northeasterly and accelerates slowly.

3) The storm to the east finds itself caught between the deepening trough to the west and the ridge to the northeast and begins to accelerate northward (northwest if the ridge to the east is strong, and northerly if weak) reaching speeds well above average.

4) Generally, a day after the westernmost tropical cyclone begins moving northeast, the easternmost storm becomes a short wave on the trough and begins its movement to the northeast. (This would be dependent on the separation distance of the two storms). This movement to the northeast can be two to three times the speed of movement of the westernmost recurved storm at the same observation time.

The synoptic considerations noted above should aid the forecaster in modifying subjectively the statistical information presented previously, as well as provide some information concerning the point of recurvature for tropical cyclones. It should be noted, however, that detailed synoptic case studies still have to be done, and it is hoped those studies will further refine the considerations already noted. These considerations, together with the results of Section 3, should help reduce the movement forecast errors for recurving tropical cyclones as well as the overall average forecast errors for all tropical cyclones in the western North Pacific.

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